Lossless Broad-Band Monolithic Microwave Active Inductors

SHINJI HARA, MEMBER, IEEE, TSUNEO TOKUMITSU, MEMBER, IEEE, AND MASAYOSHI AIKAWA, MEMBER, IEEE

Abstract —Lossless broad-band microwave active inductors for general-purpose use in microwave circuits are proposed and their characteristics are discussed. These active inductors are composed of a common-source cascode FET and a feedback FET, and operate in a wide frequency range with very low series resistance. A maximum Q factor of 65 is obtained. Theoretically, it can reach infinity. Furthermore, the inductance value can be controlled by an external voltage control.

I. Introduction

IN MMIC DESIGN, spiral inductors are often used to reduce chip size [1]–[3]. However, the area of a spiral inductor is still rather large compared to that of other lumped elements. It is also difficult to realize a broad-band spiral inductor, especially one of high inductance, because of stray capacitances. We previously proposed a microwave active inductor comprising a cascode FET and a feedback resistor for realizing wide-band MMIC's of smaller size [4]. It operates in a much higher frequency range than a spiral inductor. It is small and independent of the inductance value. However, because it includes an equivalent series resistance with a value approximately equal to the reciprocal of the GaAs FET transconductance, MMIC's where the active inductor can be applied are limited.

To overcome this limitation, we propose new types of microwave active inductors. One advantage of the newly proposed active inductors is low-loss or lossless characteristics due to the replacement of the feedback resistor by GaAs FET's, as well as the above-mentioned features realized in the previously proposed active inductor.

In this paper, further information on the previously proposed active inductor is given. The performance of the newly proposed active inductors is discussed and compared with the previously proposed active inductors and conventional spiral inductors.

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S. Hara and T. Tokumitsu are with ATR Optical and Radio Communications Research Laboratories, Sanpeidani, Inuidani, Seika-cho, Soraku-gun, Kyoto 619-01 Japan.

M. Aikawa was with ATR Optical and Radio Communications Research Laboratories, Kyoto, Japan. He is now with NTT Radio Communication Systems Laboratories, Kanagawa 238-03 Japan.

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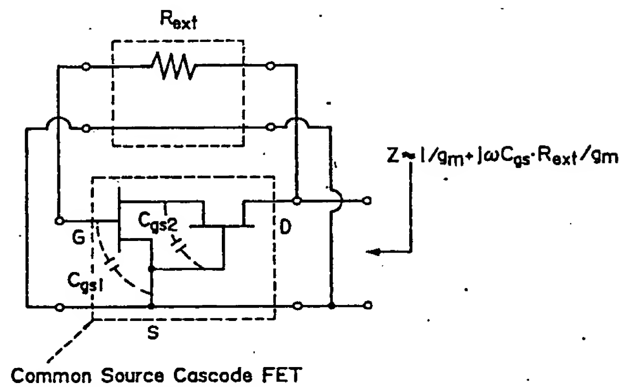


Fig. 1. Circuit configuration of the previously proposed active inductor.

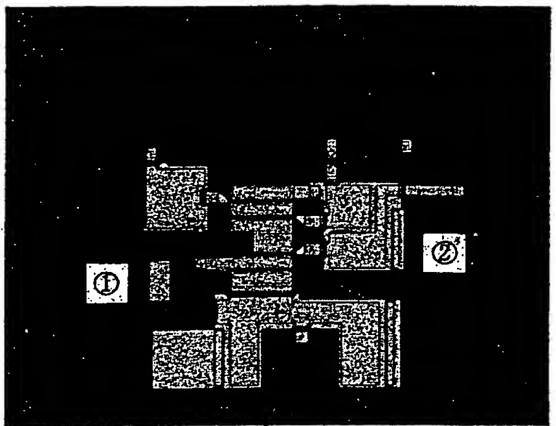
II. Previously Proposed Active Inductor

A. Configuration and Operation

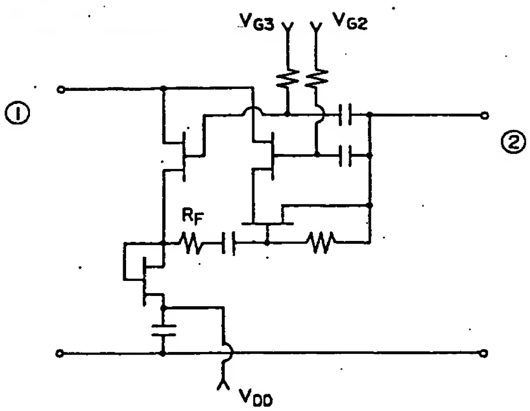
The schematic of the previously proposed microwave active inductor is shown in Fig. 1 to explain the very high frequency operation of the active inductors. This active inductor is composed of a common-source cascode FET and a parallel feedback resistor (R_{ext}), where very high frequency operation is achieved by canceling the dominant parasitic capacitances in each FET of the cascode FET. When an FET is assumed to be the combination of only the transconductance g_m and the gate–source capacitance C_{gs}, the impedance Z of this active inductor is given by

$$Z = \frac{1 + j\omega C_{gs1} R_{ext}}{g_{m1} + j\omega\left[C_{gs1} - C_{gs2}\left(\frac{g_{m1}}{g_{m2}}\right) + \omega^2 C_{gs2}\left(\frac{C_{gs1}C_{gs2}}{g_{m2}^2}\right)\right]} \quad (1)$$

where the subscripts 1 and 2 correspond to the first and second FET, respectively, in the cascode FET. When the cascode FET is composed of the same FET's with the same g_m and C_{gs}, the gate–source capacitances C_{gs1} and C_{gs2} cancel each other. This is why this active inductor operates over a wide frequency range. Operation up to 10 GHz was confirmed through measurements [4]. The resonant frequency of these active inductors increases further as the FET's high-frequency characteristics improve. An



(a)



(b)

ᶠig. 7. Schematics of the fabricated active inductor. (a) Photograph of the chip. (b) Circuit configuration.

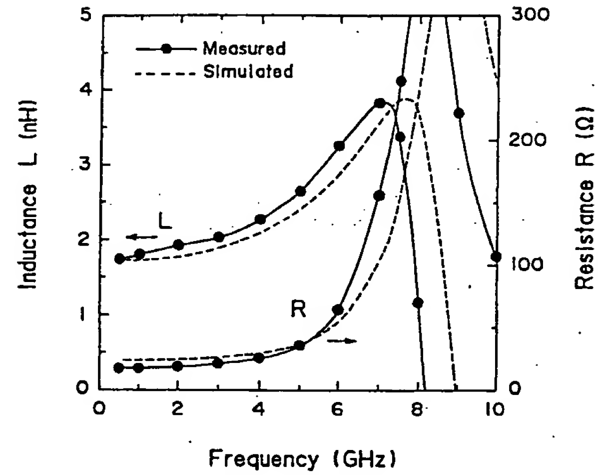


Fig. 8. Impedance–frequency characteristics of the CGF feedback active inductor. Impedance is represented by series resistance and inductance.

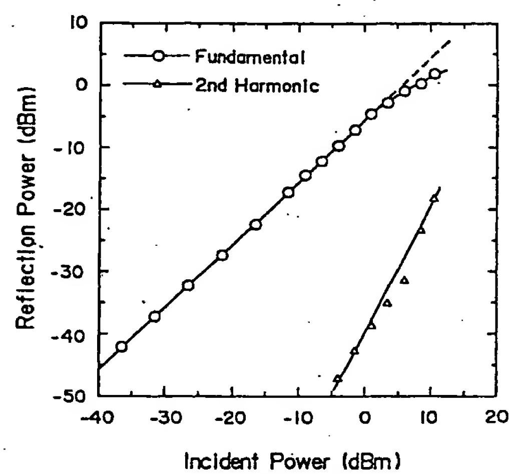


Fig. 9. Reflection power versus incident power of the active inductor.

licted in Fig. 6. This is because the FET for dc bias does ıot offer infinite impedance for the active inductor. The Q ᵣalu about 2 at 3 GHz. A higher Q value can be ›btained by using a FET with a wider gate as cascode ᶠET.

⊃. *Linearity and Distortion*

As with the resistor feedback active inductor, the current s distorted when the input voltage is higher than ($V_{S3}-$ V_{G3}), where V_{S3} and V_{G3} are the dc bias voltage of the ;ource and gate of the feedback FET. Therefore, $P_{L\max}$ is ›redicted to be about 5 dBm when 100-μm-gate-width ᶠET's are used. Fig. 9 shows the reflection power versus ncident power characteristics measured by the spectrum ınalyzer shown in Fig. 2. The circles represent the fundanental wave (2 GHz) and the triangles represent the ;econd harmonics (4 GHz). The 1 dB compression point is ıbout 5 dBm, which agrees with the predicted value. The ıandling power of the FET feedback active inductors vhich have same inductance is the same, because the nductance is determined by the gate width of the feedback ᶠET in the FET feedback active inductor.

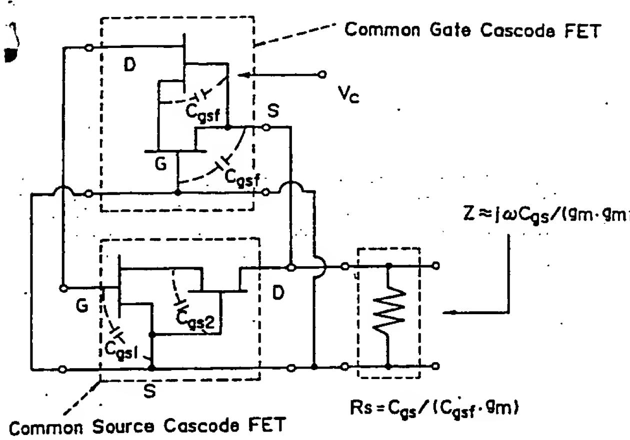
IV. Newly Proposed Active Inductor (Type (b))

A. *Configuration and Operation*

A schematic of the other type of active inductor is shown in Fig. 10. A common-gate cascode FET or a common-gate dual gate FET is used for the feedback circuit. In this case, the admittance Y of the parallel connection of a common-source cascode FET and a common-gate cascode FET is approximately expressed as follows:

$$Y=-g_m\frac{C_{gsf}}{C_{gs}}+\frac{1}{j\omega\left(\dfrac{C_{gs}}{g_m g_{mf}}\right)}. \tag{5}$$

Here, g_{mf} and C_{gsf} are, respectively, the transconductance and the gate–source capacitance of each FET in the common-gate cascode FET. Equation (5) shows that the equiv-



ig. 10. Circuit configuration of the newly proposed active inductor. The feedback circuit is a common-gate cascode FET.

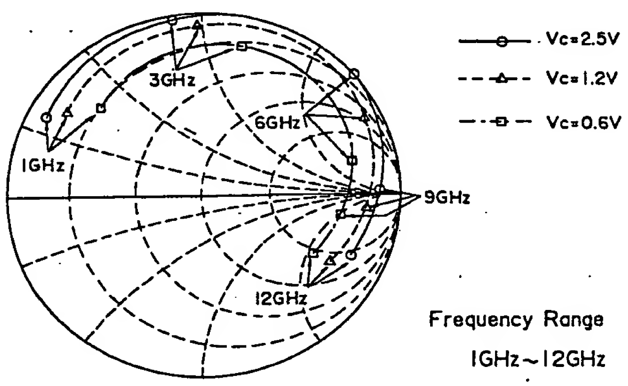


Fig. 11. Impedance change of the active inductor to the gate bias.

lent circuit of this active inductor is a parallel connection f a negative resistor ($-C_{gs}/C_{gsf}\cdot g_m$) and an inductor $C_{gs}/g_m\cdot g_{mf}$). Therefore, if a shunt resistor with a value of $_{gs}/C \cdot g_m$ is connected as shown in Fig. 10, this cir- uit . ctions as a lossless inductor whose value is $_{gs}/g_m\cdot g_{mf}$. Furthermore, the inductance value can easily e controlled by the external control voltage V_c supplied to he second gate of the feedback cascode FET, because g_{mf} controlled by V_c.

. Calculated Performance

The loss of a cascode FET feedback type active inductor an be lower than that of the CGF feedback type, as iown in (3) and (5). Furthermore, the inductance value an be changed by changing the voltage of the second gate f the feedback cascode FET. The impedance change of ie active inductor is shown in Fig. 11, where the control oltage V_c is changed. These curves are obtained from the parameters calculated by using the Curtice model in mwSPICE," where a 150-μm-gate-width common-source iscode FET and a 50-μm-gate-width common-gate cas- ode FET are used. By changing the control voltage, the iductance value changes from 2 nH to 3 nH while the ries resistance changes only from 2 Ω to 10 Ω.

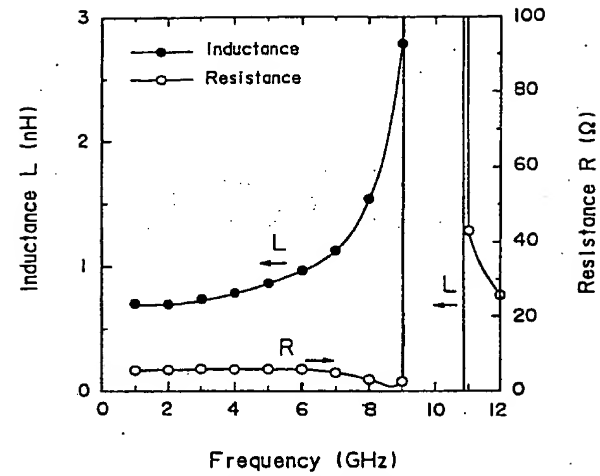


Fig. 12. Impedance–frequency characteristics of the cascode FET feed back active inductor. Impedance is represented by series resistance and inductance.

C. Experiment Result

Fig. 12 shows the measured impedance of the cascode FET feedback active inductor, where the impedance is represented by series resistance and inductance. Each FET in the active inductor has a 100 μm gate width. The maximum Q factor of 65 is obtained at about 8 GHz. Because the resistor value is selected to make the active inductor stable at all frequencies, the active inductor is somewhat lossy at lower frequency points. However, the loss is still lower than that of the CGF feedback active inductor. Furthermore, an infinite Q factor can be obtained at an even lower frequency by using a higher value shunt resistor R_S. In this case, the active inductor is potentially unstable.

V. Conclusion

Low-loss microwave active inductors have been newly proposed. These active inductors are composed of a common-source cascode FET and a feedback FET which is a common-gate FET or a common-gate cascode FET. Their low-loss characteristics are demonstrated through simulations and experiments. A maximum Q factor of 65 is obtained. The handling power of the active inductors is also demonstrated. Additionally, these active inductors are broad-band and voltage controllable. They should prove valuable in designing smaller and more efficient microwave IC's.

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Shinji Hara (M'88) was born in Toyama, Japan, in 1960. He received the B.E. and M.E. degrees in electronics engineering from Waseda University, Tokyo, Japan in 1982 and 1984, respectively.

In 1984, he joined Tokyo Research Laboratories of the Sharp Corporation, Chiba, Japan. Since September 1986, he has been a researcher at ATR Optical and Radio Communications Research Laboratories, Osaka, Japan, on leave from the Sharp Corporation. At ATR, he has been engaged in research on circuit design technologies to realize highly integrated MMIC's.

Mr. Hara is a member of the Japan Society of Applied Physics and the Institute of Electronics, Information and Communication Engineers of Japan.

Tsuneo Tokumitsu (M'88) was born in Hiroshima, Japan, in 1952. He received the B.S. and M.S. degrees in electronics engineering from Hiroshima University, Hiroshima, in 1974 and 1976, respectively.

He joined the Yokosuka Electrical Communication Laboratories, Nippon Telegraph and Telephone Public Corporation, Yokosuka, in 1976, where he did research on microwave and millimeter-wave integrated circuits, MIC's, and MMIC's and worked on the development of onboard satellite equipment. In September 1986, he joined ATR Optical and Radio Communications Research Laboratories, Osaka, where he is currently engaged in research on highly integrated MMIC's for future digital mobile communications.

Mr. Tokumitsu is a member of the Institute of Electronics, Information and Communication Engineers of Japan.

Masayoshi Aikawa (M'78) was born in Saga, Japan, on October 16, 1946. He received the B.S., M.S., and Dr. Eng. degrees in electronics engineering from Kyushu University, Fukuoka, Japan, in 1969, 1971, and 1985, respectively.

In 1971, he joined the Musashino Electrical Communication Laboratories, Nippon Telegraph and Telephone Public Corporation, Tokyo, Japan, where he did research and development work on microwave and millimeter-wave integrated circuits, MIC's, MMIC's, and equipment for 20 GHz digital radio trunk transmission systems and 26 GHz subscriber radio systems. In 1986, he joined ATR Optical and Radio Communications Research Laboratories, Osaka, Japan, where he was engaged in research on basic techniques for future digital mobile communications. He is now with the NTT Radio Communication Systems Laboratories, Yokosuka, where he has been engaged in research and development work on monolithic microwave and millimeter-wave integrated circuits and their applications.

Dr. Aikawa is a member of the Institute of Electronics, Information and Communication Engineers of Japan.